Compatibility of Exotic States with Neutron Star Observation

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We consider the effect of hard core repulsion in the baryon-baryon interaction at short distance to the properties of a neutron star. We obtain that, even with hyperons in the interior of a neutron star, the neutron star mass can be as large as $\sim 2M_\odot$.

§1. Introduction

Reports on recent observations of pulsars in various binary systems show that the maximum mass of a neutron star can be large as $(1.7 \sim 2.1)M_\odot$.[1),2)] Most of them still have large uncertainty, but a few are within the above range with relatively small error bars. The possibility of large mass of a neutron star thus has led to a claim that exotic states of matter at high densities are not necessary in the neutron star as far as its mass is concerned,[3)] but there also appeared a counter argument that the large mass does not necessarily rule out the exotic states.[4)] There are many sources of uncertainties at high densities, *e.g.* state of matter, constituent particles and their interactions, but the information available to reduce the uncertainties is not sufficient yet.

We revisit the neutron star mass problem with a simple phenomenological approach. One fixed point of nuclear matter physics is the nuclear saturation density; its properties such as density, binding energy, symmetry energy, and compression modulus are fairly well constrained. We describe these saturation properties in terms of quantum hadrodynamics (QHD).[5)] The other fixed point we choose is the hard core repulsion at short range. Though it is a kind of artifact adopted to describe the nucleon-nucleon data, its role is clear in many phenomena of nuclear physics. The effect of hard core can be parametrized with an excluded volume in the estimation of thermodynamic variables.[6),7),8)] It has been more frequently employed to explain the phase transition in the relativistic heavy ion collision environment, and could describe well the transition from hadronic to quark-gluon plasma phase.[9)]

In this work, by including hard cores in the interaction of baryons, we explore the bulk properties of the neutron star, and compare the result with the recent observation of heavy neutron star masses. This paper is outlined as follows. In the next section, we briefly address the basic formalism of QHD with hard core. The next section comes up with numerical results, and brief concluding remarks are drawn in the following section.

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§2. Formalism

We employ the QHD Lagrangian,

$$\begin{aligned}\mathcal{L} &= \sum_B \bar{\psi}_B \left(i\partial\cdot\gamma - m_B + g_{\sigma B}\sigma - g_{\omega B}\gamma_0\omega_0 - g_{\rho B}\tau_3\gamma_0 b_{30}\right)\psi_B \\ &-\frac{1}{2}m_\sigma^2\sigma^2 + \frac{1}{2}m_\omega^2\omega_0^2 + \frac{1}{2}m_\rho^2 b_{30}^2 - \frac{b}{3}m_N(g_{\sigma N}\sigma)^3 - \frac{c}{4}(g_{\sigma N}\sigma)^4 \\ &+ \sum_{l=e,\,\mu}\bar{\psi}_l(i\partial\cdot\gamma - m_l)\psi_l, \end{aligned} \tag{2·1}$$

where the baryon species B includes octet baryons, and σ, ω_0 and b_{30} are non-vanishing meson fields in the mean field approximation. When we account for the forbidden region due to hard core, the baryon density is redefined as

$$\rho = \frac{\rho'}{1 + v_{\rm ev}\rho'}, \tag{2·2}$$

where ρ' is the density in the case of point particle and $v_{\rm ev}$ the excluded volume. We assume $v_{\rm ev} = \frac{4}{3}\pi r_0^3$ where r_0 is the radius of hard core, which is treated as a free parameter in our consideration. Consistency with thermodynamic relations and self-consistency conditions alter the form of state variables (pressure, chemical potential, energy density and etc) and equation of motion of σ-meson field from those of point particle ones. The explicit formulas and equations can be found in old[6),7),8)] and recent[10),11)] publications.

Three meson-nucleon coupling constants $g_{\sigma N}$, $g_{\omega N}$ and $g_{\rho N}$ and two σ-meson self interaction coefficients b and c are fitted to five saturation properties, the saturation density (0.17 fm^{-3}), binding energy (16.0 MeV), symmetry energy (32.5 MeV), compression modulus (300 MeV) and nucleon effective mass ($0.75 m_N^*$), with a given hard core radius r_0. Meson-hyperon coupling constants are determined by quark counting rules, $g_{MY} = g_{MN}\sum_{q=u,d} n_{qY}/3$, where g_{MY} is the meson-hyperon coupling constant, n_{qY} is the number of u and d quarks in a hyperon species Y and g_{MN} is the meson-nucleon coupling constant. As for the hard core radius of hyperons, we assume the same value as that of the nucleon for simplicity.

Table I summarizes the parameters determined from the given saturation properties and hard core radii.

r_0 (fm)	$g_{\sigma N}$	$g_{\omega N}$	$g_{\rho N}$	$b\,(\times 10^3)$	$c\,(\times 10^3)$
0	8.44	8.92	7.76	3.97	4.00
0.2	8.43	8.91	7.72	3.80	4.37
0.3	8.39	8.89	7.64	3.38	5.26
0.4	8.30	8.85	7.47	2.51	7.11
0.5	8.16	8.78	7.19	0.93	10.47

Table I. Meson-nucleon coupling constants and coefficients b and c fitted to a set of saturation properties described in the text with a given r_0 value.

§3. Numerical result

Fig. 1 shows the binding energy per a nucleon in the symmetric nuclear matter with different hard core radii. Though the saturation properties are the same regardless of r_0 values, the equation of state becomes stiffer at high densities with a larger r_0 value.

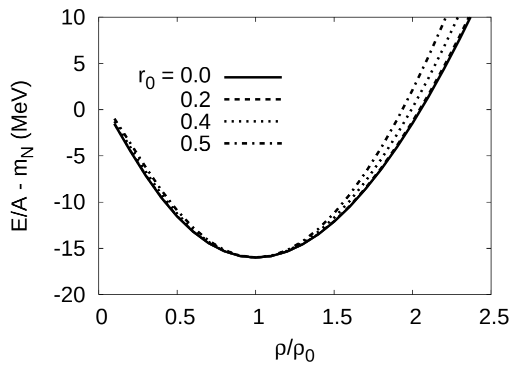

Fig. 1. Binding energy of a nucleon in the symmetric nuclear matter with different hard core radii.

The equation of state of neutron star matter is determined self-consistently by the baryon number conservation, charge neutrality, β-equilibrium of baryons and leptons, and equations of motion of meson fields. Once the equation of state is determined, the mass-radius relation of a neutron star can be obtained by solving Tolman-Oppenheimer-Volkoff (TOV) equation. Table II shows the maximum mass of a neutron star, corresponding radius and central density with nucleons only (columns of "*np*") and with hyperons (columns of "*npY*"). Consistent with the behavior of the equation of state at high densities in Fig. 1, the maximum mass becomes larger with a larger r_0 value. For *np* case, when $r_0 = 0.5$ fm, the increase amounts to 10% of the maximum mass without hard core. With hyperons, the maximum mass increases to the range of large mass in recent observations when $r_0 \gtrsim 0.3$ fm.

	np			npY		
r_0 (fm)	M ($M_\odot$)	R (km)	$\rho_{\rm cent}$ (ρ_0)	M ($M_\odot$)	R (km)	$\rho_{\rm cent}$ (ρ_0)
0	2.10	10.9	6.4	1.53	11.3	6.1
0.2	-	-	-	1.58	11.4	6.1
0.3	2.14	11.1	6.2	1.70	11.5	5.9
0.4	2.20	11.4	5.9	1.97	12.2	5.2
0.5	2.34	11.7	5.4	-	-	-

Table II. Maximum mass M in units of solar mass, and corresponding radius R in km and central density $\rho_{\rm cent}$ in unit of the saturation density ρ_0.

§4. Conclusion

We investigated the maximum mass of a neutron star in a simple phenomenological approach where the hard-core repulsion is included in the QHD model. The hard core radius is treated as a free parameter, and the meson-nucleon coupling constants are fixed identical saturation properties. We obtained the equation of state of neutron star matter that satisfies thermodynamic equations and self-consistency conditions. Solving TOV equation, we obtained the mass-radius relation of a neutron star. Our result shows that the maximum mass with hyperons can be as large as observed masses with a hard core radius $r_0 \gtrsim 0.3$ fm. These values of r_0 are in the range of hard core radius $0.3 \sim 0.6$ fm in well-known hard-core potential models such as Hamada-Johnston[12] or Reid.[13] More investigations are necessary to figure out the uncertainties. For instance, the hard core size of hyperons can matter. The effect of hard cores to the formation of other exotic states such as meson condensation or deconfined quark phases is also worthy to be studied.

To conclude, the our result shows that the hyperon matter, which is known to give the biggest effect to the mass-radius relation of a neutron star among possible exotic states in the interior of a neutron star, is not necessarily incompatible with the observed mass.

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